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## Young Massive Clusters in Merging and Starburst Galaxies

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**Abstract.** The currently available empirical evidence on the star formation processes in the extreme, high-pressure environments induced by galaxy encounters, mostly based on high-resolution *Hubble Space Telescope* imaging observations, strongly suggests that star *cluster* formation is an important and perhaps even the dominant mode of star formation in the starburst events associated with galaxy interactions. The production of young massive star clusters (YSCs) seems to be a hallmark of intense star formation, particularly in interacting and starburst galaxies. Their sizes, luminosities, and mass estimates are entirely consistent with what is expected for young Milky Way-type globular clusters (GCs). YSCs are important because of what they can tell us about GC formation and evolution (e.g., initial characteristics and early survival rates). They are also of prime importance as probes of the formation and (chemical) evolution of their host galaxies, and of the initial mass function in the extreme environments required for cluster formation. Recent evidence lends support to the scenario that Milky Way-type GCs (although more metal rich), which were once thought to be the oldest building blocks of galaxies, are still forming today.

### 1. Extreme environmental conditions

Stars rarely form in isolation. In fact, it is well known that the vast majority of stars in the Galaxy, and also in nearby galaxies, are found in groups ranging from small associations, containing some  $100 M_{\odot}$ , to compact, old “globular” and young massive clusters. The nearest examples of these latter objects include the Galactic star-forming regions NGC 3603 and Westerlund 1, and the giant starburst region 30 Doradus with its central star cluster R136 in the Large Magellanic Cloud.

Although the older Galactic *open* clusters (with ages of several Gyr) are undoubtedly gravitationally bound objects, their lower masses compared to the globular cluster population, and more diffuse structures make them much more vulnerable to disk (and bulge) shocking when they pass through the Galactic disk (or close to the bulge), thus leading to enhanced cluster evaporation. These objects are therefore unlikely globular cluster progenitors. It appears that the conditions for the formation of compact, massive star clusters – that have the potential to eventually evolve into globular cluster-type objects by the time they reach a similar age – are currently not present in the Galaxy, or at best to a very limited extent (e.g., Westerlund 1; Hanson 2003).

The production of luminous, massive yet compact star clusters seems to be a hallmark of the most intense star-forming episodes, or starbursts. The defining

properties of young massive star clusters (YSCs; with masses often significantly in excess of  $M_{\text{cl}} = 10^5 M_{\odot}$ ) have been explored in intense starburst regions in several dozen galaxies, often involved in gravitational interactions of some sort (e.g., Holtzman et al. 1992, Whitmore et al. 1993, O’Connell et al. 1994, Conti et al. 1996, Watson et al. 1996, Carlson et al. 1998, de Grijs et al. 2001, 2003a,b,c,d,e).

An increasingly large body of observational evidence suggests that a large fraction of the star formation in starbursts actually takes place in the form of such concentrated clusters, rather than in small-scale star-forming “pockets”. YSCs are therefore important as benchmarks of cluster formation and evolution. They are also important as tracers of the history of star formation of their host galaxies, their chemical evolution, the initial mass function (IMF), and other physical characteristics in starbursts.

In a detailed study of the young star cluster population associated with the fading starburst region “B” in the prototype nearby starburst galaxy M82 (de Grijs et al. 2001), we concluded that the last tidal encounter between M82 and its large neighbour spiral galaxy M81, which occurred about 500 – 800 Myr ago (Brouillet et al. 1991, Yun 1999) had a major impact on what was probably an otherwise normal, quiescent, disk galaxy. It caused a concentrated starburst, resulting in a pronounced peak in the clusters’ age distribution, roughly 1 Gyr ago (de Grijs et al. 2001, 2003c, Parmentier et al. 2003). The enhanced cluster formation decreased rapidly, within a few hundred Myr of its peak. However, general star formation activity continued in the galactic disk of M82’s region B, probably at a much lower rate, until  $\sim 20$  Myr ago.

The evidence for the decoupling between cluster and field star formation is consistent with the view that star cluster formation requires special conditions, such as large-scale gas flows, in addition to the presence of dense gas (cf. Ashman & Zepf 1992, Elmegreen & Efremov 1997). Such conditions occur naturally in the extreme environments of gravitationally interacting galaxies.

Using optical observations of the “Mice” and “Tadpole” interacting galaxies (NGC 4676 and UGC 10214, respectively) – based on a subset of the Early Release Observations obtained with the *Advanced Camera for Surveys* on board the *Hubble Space Telescope (HST)* – and the novel technique of pixel-by-pixel analysis of their colour-colour and colour-magnitude diagrammes, we deduced the systems’ star and star cluster formation histories (de Grijs et al. 2003e).

In both of these interacting systems we find several dozen YSCs (or, alternatively, compact star-forming regions), which overlap spatially with regions of active star formation in the galaxies’ tidal tails and spiral arms (from a comparison with  $H\alpha$  observations that trace active star formation; Hibbard & van Gorkom 1996). We estimate that the main gravitational interactions responsible for the formation of these clusters occurred  $\sim 150 - 200$  Myr ago.

In fact, we show that star cluster formation is a major mode of star formation in galactic interactions, with  $\geq 35\%$  of the active star formation in encounters occurring in star clusters (de Grijs et al. 2003e). The tidal tail of the Tadpole system is dominated by star forming regions, which contribute  $\sim 70\%$  of the total flux in the *HST I*-band filter (decreasing to  $\sim 40\%$  in the equivalent *B*-band filter). If the encounter occurs between unevenly matched, gas-rich galaxies then, as expected, the effects of the gravitational interaction are much

more pronounced in the smaller galaxy. For instance, when we compare the impact of the interaction as evidenced by star cluster formation between M82 (de Grijs et al. 2001, 2003b,c) and M81 (Chandar et al. 2001), or the star cluster formation history in the “Whirlpool Galaxy” M51 (Bik et al. 2003), which is currently in the process of merging with the smaller spiral galaxy NGC 5194, the evidence for enhanced cluster formation in the larger galaxy is minimal if at all detectable.

The NGC 6745 system represents a remarkably violently star-forming interacting pair of unevenly matched galaxies. The optical morphology of NGC 6745, and in particular the locations of the numerous bright blue star-forming complexes and compact cluster candidates, suggest a recent tidal passage by the small northern companion galaxy (NGC 6745c; nomenclature from Karachentsev et al. 1978) across the eastern edge of the main galaxy, NGC 6745a. The high relative velocities of the two colliding galaxies likely caused ram pressure at the surface of contact between both galaxies, which – in turn – is responsible for the triggering of enhanced star and cluster formation, most notably in the interaction zone in between the two galaxies, NGC 6745b (cf. de Grijs et al. 2003a). The smaller galaxy, however, does not show any significant enhanced cluster formation, which is most likely an indication that it contains very little gas.

For the NGC 6745 young cluster system we derive a median age of  $\sim 10$  Myr. Based on the age distribution of the star clusters, and on the HI morphology of the interacting system, we confirm the interaction-induced enhanced cluster formation scenario once again. NGC 6745 contains a significant population of high-mass clusters, with masses in the range  $6.5 \leq \log(M_{\text{cl}}/M_{\odot}) \leq 8.0$ . These clusters do not have counterparts among the Galactic globular clusters (e.g., Mandushev et al. 1991, Pryor & Meylan 1993), but are similar to or exceed the spectroscopically confirmed mass estimates of the “super star clusters” (SSCs) in M82 (e.g., M82 F and L; see Smith & Gallagher 2001) and the Antennae galaxies (Mengel et al. 2002). We caution, however, that these massive SSC candidates may not be gravitationally bound objects, but more diffuse star forming regions or aggregates of multiple unresolved clusters instead. Nevertheless, we measure a very compact effective radius for the most massive object ( $M_{\text{cl}} \simeq 5.9 \times 10^8 M_{\odot}$ ) of only  $R_{\text{eff}} \sim 16$  pc. However, this object appears very elongated, or may in fact be a double cluster. We should also keep in mind that this high mass estimate is a strong function of the (low) metallicity assumed; if we had assumed (higher) solar metallicity for this object, the derived age would have been significantly smaller ( $\sim 10 - 20$  Myr vs.  $\sim 1$  Gyr assumed in our study), and the mass could be smaller by a factor of  $\gtrsim 10$ . Even so, if we could confirm this mass estimate spectroscopically, either of the subcomponents would be the most massive cluster known to date, significantly exceeding cluster W3 in NGC 7252, which has a mass of about  $(3 - 18) \times 10^7 M_{\odot}$ , depending on the age, metallicity and IMF assumed (Schweizer & Seitzer 1998; Maraston et al. 2001, 2004). Our detection of such massive SSCs in NGC 6745, which are mostly located in the intense interaction zone, supports the scenario that such objects form preferentially in the extreme environments of interacting galaxies.

## 2. An evolutionary connection?

The (statistical) derivation of galaxy formation and evolution scenarios using their star cluster systems as tracers is limited to the study of integrated cluster properties for all but the nearest galaxies, even at *HST* spatial resolution.

The question remains, therefore, whether or not at least a fraction of the YSCs seen in abundance in extragalactic starbursts, are potentially the progenitors of globular cluster-type objects in their host galaxies. If we could settle this issue convincingly, one way or the other, the implications of such a result would have profound and far-reaching implications for a wide range of astrophysical questions, including (but not limited to) our understanding of the process of galaxy formation and assembly, and the process and conditions required for star (cluster) formation. Because of the lack of a statistically significant sample of similar nearby objects, however, we need to resort to either statistical arguments or to the painstaking approach of one-by-one studies of individual objects in more distant galaxies. With the ever increasing number of large-aperture ground-based telescopes equipped with state-of-the-art high-resolution spectroscopic detectors and the wealth of observational data provided by the *HST*, we may now be getting close to resolving this important issue. It is of paramount importance, however, that theoretical developments go hand in hand with observational advances.

The present state-of-the-art teaches us that the sizes, luminosities, and – in several cases – spectroscopic mass estimates of most (young) extragalactic star cluster systems are fully consistent with the expected properties of young Milky Way-type globular cluster progenitors (e.g., Meurer 1995, van den Bergh 1995, Ho & Filippenko 1996a,b, Schweizer & Seitzer 1998, de Grijs et al. 2001, 2003d). For instance, for the young massive star cluster system in the centre of the nearby starburst spiral galaxy NGC 3310, we find a median mass of  $\langle \log(M_{\text{cl}}/M_{\odot}) \rangle = 5.24 \pm 0.05$  (de Grijs et al. 2003d); their mass distribution is characterised by a Gaussian width of  $\sigma_{\text{Gauss}} \simeq 0.33$  dex. In view of the uncertainties introduced by the poorly known lower-mass slope of the stellar IMF ( $m_* \leq 0.5M_{\odot}$ ), our median mass estimate of the NGC 3310 cluster system – which was most likely formed in a (possibly extended) global burst of cluster formation  $\sim 3 \times 10^7$  yr ago – is remarkably close to that of the Galactic globular cluster system (cf. de Grijs et al. 2003d; Fig. 1).

However, the postulated evolutionary connection between the recently formed massive star clusters in regions of violent star formation and starburst galaxies, and old globular clusters in the nearby Universe is still a contentious issue. The evolution and survivability of young clusters depend crucially on the stellar IMF of their constituent stars (cf. Smith & Gallagher 2001): if the IMF is too shallow, i.e., if the clusters are significantly depleted in low-mass stars compared to (for instance) the solar neighbourhood, they will disperse within a few orbital periods around their host galaxy’s centre, and likely within about a Gyr of their formation (e.g., Smith & Gallagher 2001, Mengel et al. 2002).

Ideally, one would need to obtain (i) high-resolution spectroscopy (e.g., with 8m-class ground-based telescopes) of all clusters in a given cluster sample in order to obtain dynamical mass estimates (assuming that the clusters are in full virial equilibrium), and (ii) high-resolution imaging (e.g., with the *HST*) to measure their luminosities. One could then estimate the mass-to-light (M/L)

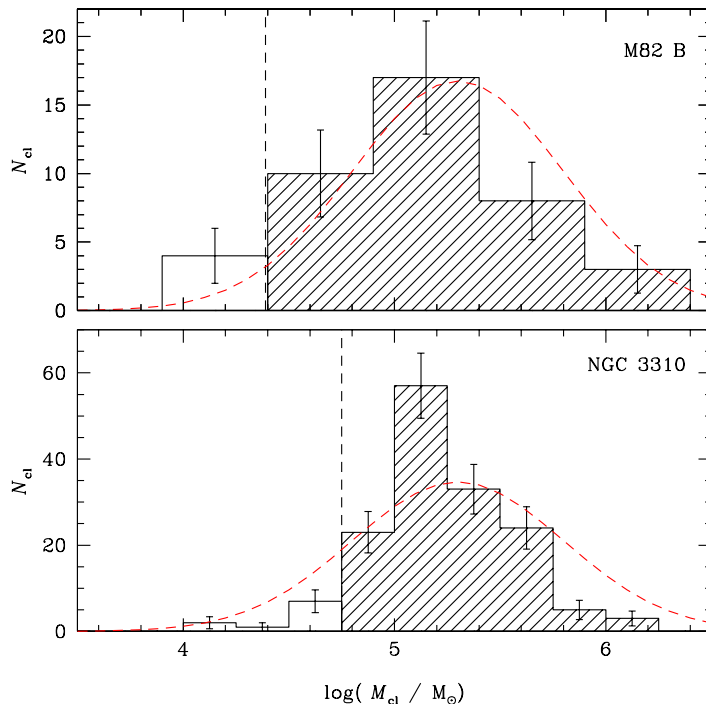


Figure 1. Mass distributions of the intermediate-age,  $\sim 1$  Gyr-old star clusters in M82 B (*top*), and the young ( $\sim 30$  Myr-old) cluster population dominating the central regions of the starburst galaxy NGC 3310 (*bottom*). For comparison, the dashed Gaussian distributions show the mass distribution of the Galactic globular cluster system, normalised to the same number of clusters in each population. The vertical dashed lines indicate our 50 per cent completeness limits, with severe incompleteness affecting the clusters populating the open histograms.

ratios for each cluster, and their ages from the spectra. The final, crucial analysis would involve a direct comparison between the clusters’ locations in the M/L ratio vs. age diagramme with models of “simple stellar populations” governed by a variety of IMF descriptions (cf. Smith & Gallagher 2001, Mengel et al. 2002).

However, individual young star cluster spectroscopy, feasible today with 8m-class telescopes for the nearest systems, is very time-consuming, since observations of large numbers of clusters are required to obtain statistically significant results. Instead, one of the most important and most widely used diagnostics, both to infer the star (cluster) formation history of a given galaxy, and to constrain scenarios for its expected future evolution, is the distribution of cluster luminosities, or – alternatively – their associated masses, commonly referred to as the cluster luminosity and mass functions (CLF, CMF), respectively.

Starting with the seminal work by Elson & Fall (1985) on the young cluster system in the Large Magellanic Cloud (with ages  $\leq 2 \times 10^9$  yr), an ever increasing body of evidence seems to imply that the CLF of YSCs is well described by a

power law down to the lowest luminosities (and thus masses). On the other hand, for the old globular cluster systems in the local Universe, with ages  $\geq 10$  Gyr, the CLF shape is well established to be roughly Gaussian (Whitmore et al. 1995, Harris 1996, 2001, Harris et al. 1998). This shape is almost universal, showing only a weak dependence on the metallicity and mass of the host galaxy (e.g., Harris 1996, 2001, Whitmore et al. 2002).

This type of observational evidence has led to the popular – but thus far mostly speculative – theoretical prediction that not only a power-law, but *any* initial CLF (and CMF) will be rapidly transformed into a Gaussian distribution because of (i) stellar evolutionary fading of the lowest-luminosity (and therefore lowest-mass) clusters to below the detection limit; and (ii) disruption of the low-mass clusters due both to interactions with the gravitational field of the host galaxy, and to cluster-internal two-body relaxation effects (such as caused by star-star collisions and the resulting redistribution of mass inside the cluster) leading to enhanced cluster evaporation (e.g., Elmegreen & Efremov 1997, Gnedin & Ostriker 1997, Ostriker & Gnedin 1997, Fall & Zhang 2001).

We recently reported the first discovery of an approximately Gaussian CLF (and CMF) for the star clusters in M82 B formed roughly simultaneously in a pronounced burst of cluster formation (de Grijs et al. 2003b,c). This provides the very first sufficiently deep CLF (and CMF) for a star cluster population at intermediate age (of  $\sim 1$  billion years), which thus serves as an important benchmark for theories of the evolution of star cluster systems (but see Goudfrooij, this volume).

The shape of the CLF (CMF) of young cluster systems has recently attracted renewed theoretical and observational attention. Various authors have pointed out that for young star clusters exhibiting an age range, one must first correct their CLF to a common age before a realistic assessment of their evolution can be achieved (e.g., Meurer 1995, Fritze-v. Alvensleben 1998, 1999, de Grijs et al. 2001, 2003b,c). This is particularly important for young cluster systems exhibiting an age spread that is a significant fraction of the system’s median age, because of the rapid evolution of the colours and luminosities of star clusters at young ages (below  $\sim 1$  Gyr). Whether the observed power laws of the CLF and CMF for young star cluster systems are intrinsic to the cluster population or artefacts due to the presence of an age spread in the cluster population – which might mask a differently shaped underlying distribution – is therefore a matter of debate (see, e.g., Carlson et al. 1998, Zhang & Fall 1999, Vesperini 2000, 2001).

Nevertheless, the CLF shape and characteristic luminosity of the M82 B cluster system is nearly identical to that of the apparently universal CLFs of the old globular cluster systems in the local Universe (e.g., Whitmore et al. 1995, Harris 1996, 2001, Ashman & Zepf 1998, Harris et al. 1998). This is likely to remain virtually unchanged for a Hubble time, if the currently most popular cluster disruption models hold. With the very short characteristic cluster disruption time-scale governing M82 B (de Grijs et al. 2003c), its cluster mass distribution will evolve towards a higher characteristic mass scale than that of the Galactic globular cluster system by the time it reaches a similar age. Thus, this evidence, combined with the similar cluster sizes (de Grijs et al. 2001), lends strong support to a scenario in which the current M82 B cluster population will

eventually evolve into a significantly depleted old Milky Way-type globular cluster system dominated by a small number of high-mass clusters. However, they will likely be more metal-rich than the present-day old globular cluster systems.

The connection between young or intermediate-age star cluster systems, as in M82 B, and old globular clusters lends support to the hierarchical galaxy formation scenario. Old globular clusters were once thought to have been formed at the time of, or before, galaxy formation, i.e., during the first galaxy mergers and collisions. However, we have now shown that the evolved CLF of the compact star clusters in M82 B most likely to survive for a Hubble time will probably resemble the high-mass wing of the “universal” old globular cluster systems in the local Universe. Proto-globular cluster formation thus appears to be continuing until the present.

### 3. The bottom line

In summary, in this review I have shown that young, massive star clusters are the most significant end products of violent star-forming episodes (starbursts) triggered by galaxy collisions and gravitational interactions in general. Their contribution to the total luminosity induced by such extreme conditions dominates, by far, the overall energy output due to the gravitationally-induced star formation. The general characteristics of these newly-formed clusters (such as their ages, masses, luminosities, and sizes) suggest that at least a fraction may eventually evolve into equal, or perhaps slightly more massive, counterparts of the abundant old globular cluster systems in the local Universe, although they will likely be more metal rich than the present generation of globular clusters. Establishing whether or not such an evolutionary connection exists requires our detailed knowledge of not only the physics underlying the evolution of “simple” stellar populations (i.e., idealised model clusters), but also that of cluster disruption in the time-dependent gravitational potentials of interacting galaxies. Initial results seem to indicate that proto-globular clusters do indeed continue to form today, which would support hierarchical galaxy formation scenarios. Settling this issue conclusively will have far-reaching consequences for our understanding of the process of galaxy formation and assembly, and of star formation itself, both of which processes are as yet poorly understood.

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### References

- Ashman K.M., Zepf S.E., 1992, *ApJ*, 384, 50
- Ashman K.M., Zepf S.E., 1998, *Globular Cluster Systems*, Cambridge University Press
- Bik A., Lamers H.J.G.L.M., Bastian N., Panagia N., Romaniello M., 2003, *A&A*, 397, 473
- Brouillet N., Baudry A., Combes F., Kaufman M., Bash F., 1991, *A&A*, 242, 35
- Carlson M.N., et al., 1998, *AJ*, 115, 1778
- Chandar R., Ford H.C., Tsvetanov Z., 2001, *AJ*, 122, 1330
- Conti P.S., Leitherer C., Vacca W.D., 1996, *ApJ*, 461, L87

- de Grijs R., O'Connell R.W., Gallagher J.S., 2001, *AJ*, 121, 768
- de Grijs R., Anders P., Lynds R., Bastian N., Lamers H.J.G.L.M., Fritze-v. Alvensleben U., 2003a, *MNRAS*, 343, 1285
- de Grijs R., Bastian N., Lamers, H.J.G.L.M., 2003b, *ApJ*, 583, L17
- de Grijs R., Bastian N., Lamers H.J.G.L.M., 2003c, *MNRAS*, 340, 197
- de Grijs R., Fritze-v. Alvensleben U., Anders P., Gallagher J.S., Bastian N., Taylor V.A., Windhorst R.A., 2003d, *MNRAS*, 342, 259
- de Grijs R., Lee J.T., Mora Herrera M.C., Fritze-v. Alvensleben U., Anders P., 2003e, *New Astron.*, 8, 155
- Elmegreen B.G., Efremov Y.N., 1997, *ApJ*, 480, 235
- Elson R.A.W., Fall S.M., 1985, *PASP*, 97, 692
- Fall S.M., Zhang Q., 2001, *ApJ*, 561, 751
- Fritze-v. Alvensleben U., 1998, *A&A*, 336, 83
- Fritze-v. Alvensleben U., 1999, *A&A*, 342, L25
- Gnedin O.Y., Ostriker J.P., 1997, *ApJ*, 474, 223
- Hanson M.M., 2003, *ApJ*, 597, 957
- Harris W.E., 1996, *AJ*, 112, 1487
- Harris W.E., 2001, in: *Star Clusters*, Saas-Fee Advanced Course 28, Springer-Verlag, 223
- Harris W.E., Harris G.L.H., McLaughlin D.E., 1998, *AJ*, 115, 1801
- Hibbard J.E., van Gorkom J.H., 1996, *AJ*, 111, 655
- Ho L.C., Filippenko A.V., 1996a, *ApJ*, 466, L83
- Ho L.C., Filippenko A.V., 1996b, *ApJ*, 472, 600
- Holtzman J.A., et al., 1992, *AJ*, 103, 691
- Karachentsev I.D., Karachentseva V.E., Shcherbanovskii A.L., 1978, *PAZh*, 4, 483 (English transl. in *Soviet Astr. Lett.*, 4, 261)
- Mandushev G., Spassova N., Staneva A., 1991, *A&A*, 252, 94
- Maraston C., Kissler-Patig M., Brodie J.P., Barmby P., Huchra J.P., 2001, *A&A*, 370, 176
- Maraston C., Bastian N., Saglia R.P., Kissler-Patig M., Schweizer F., Goudfrooij P., 2004, *A&A*, in press (astro-ph/0311232)
- Mengel S., Lehnert M.D., Thatte N., Genzel R., 2002, *A&A*, 383, 137
- Meurer G.R., 1995, *Nat.*, 375, 742
- O'Connell R.W., Gallagher J.S., Hunter D.A., 1994, *ApJ*, 433, 65
- Ostriker J.P., Gnedin O.Y., 1997, *ApJ*, 487, 667
- Parmentier G., de Grijs R., Gilmore G.F., 2003, *MNRAS*, 342, 208
- Pryor C., Meylan G., 1993, in: *Structure and Dynamics of Globular Clusters*, Djorgovski S.G., Meylan G., eds., San Francisco: ASP, p. 357
- Schweizer F., Seitzer P., 1998, *AJ*, 116, 2206
- Smith L.J., Gallagher J.S., 2001, *MNRAS*, 326, 1027
- van den Bergh S., 1995, *Nat.*, 374, 215
- Vesperini E., 2000, *MNRAS*, 318, 841
- Vesperini E., 2001, *MNRAS*, 322, 247
- Watson A.M., et al., 1996, *AJ*, 112, 534
- Whitmore B.C., Schweizer F., Kundu A., Miller B.W., 2002, *AJ*, 124, 147
- Whitmore B.C., Schweizer F., Leitherer C., Borne K., Robert C., 1993, *AJ*, 106, 1354
- Whitmore B.C., Sparks W.B., Lucas R.A., Macchetto F.D., Biretta J.A., 1995, *ApJ*, 454, L73
- Yun M.S., 1999, *IAU Symp. 186: Galaxy Interactions at Low and High Redshift*, Barnes J.E., Sanders D.B., eds., p. 81
- Zhang Q., Fall S.M., 1999, *ApJ*, 527, L81